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USS *Bunker Hill* (CG 52) receives fuel from USS *Carl Vinson* (CVN 70) during a refueling at sea.

TAKING WAVE PREDICTION TO NEW LEVELS:
WAVEWATCH III

STRUCTURE CAN EMERGE FROM CHAOS WITH A LITTLE HELP.

By James D. Dykes, W. Erick Rogers, and Ruth H. Preller

To provide more effective meteorological and oceanographic support to the U.S. Navy, the Naval Research Laboratory (NRL) has transitioned state-of-the-art operational wave prediction technology to the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi, and to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) at Monterey, California. Developed at the National Oceanic and Atmospheric Administration (NOAA), and used for civilian prediction at the National Weather Service, the WAVEWATCH III® numerical wave prediction model—featuring multigrid operability among other improvements—was tailored for the Navy's unique military demands, tested, evaluated for operational use in 2013, and declared operational in August 2014. The Navy system runs daily on high-performance machines at the Navy Department of Defense Supercomputing Resource Center.

Operational Support to the Navy

Large-scale wave models have a number of applications operationally, such as ship routing and high seas warnings. The most severe storms can generally be avoided by ships using meteorological forecasts, but a wave model improves prediction of wind waves by integrating effects of fetch, duration, and turning winds, and is essential to anticipate the swells emanating from these storms. Certain operations, such as ship-to-ship transfers of materiel, can be particularly sensitive to long swells. Forecasts of these conditions can be vital for operations planning. Knowledge of the general wave conditions helps trim costs in ship transit. Products from WAVEWATCHIII, suited for these kinds of operations, include forecasts of wave height, direction and period (including swell), wave steepness scaled to platform size, and a crossing sea metric that defines regions with significant wave energy approaching from multiple directions.

Wave model forecast products used by the Navy do not only address large-scale requirements. Coastal, high-resolution wave and wave-affected predictions are essential to supporting numerous specialized Navy missions in the littorals, the areas for which forecast operations at NAVOCEANO are well suited. Directional wave spectral parameters from the global and regional domains are passed on to increasingly smaller domains along their boundaries for wave simulations performed by a variety of modeling systems. The smaller domain applications of these systems are used to resolve features such as surf and rip currents, conditions that affect special operations, amphibious assaults, and logistics over the shore. Changes in ocean optics due to re-suspended sediments caused by wave affects in the bottom boundary layer are especially important for diver visibility and mine countermeasures. Wave effects on harbors also are a concern for docked vessels in spite of the normally protective barriers.

Multigrid Approach

The Navy's current version of WAVEWATCHIII features the capability of operating with gridded domains of multiple resolution simultaneously, ranging from 0.1-degree grid spacing in various coastal areas around the world to 0.5-degree spacing for the rest of the globe. Most of the higher resolution domains simply provide the complete coverage for the entire rectangular area. But, the domain around Australia is tailored for coverage near the coastline using a new capability that masks out offshore (open water) computational points, where the coarser global grid is used instead, saving computational cycles. All modeled waves are generated by surface winds that come from the synoptic scale meteorological models run at FNMOC. Many of the regional wave model domains receive winds from the Coupled Ocean/ Atmosphere Mesoscale Prediction System (COAMPSTM) models. Anywhere on the globe where COAMPSTM is not run, the model uses the winds from NAVGEM, the Navy's global spectral model for worldwide weather coverage.

Traditional modeling systems have been based on coarse grids covering large regions and smaller, finer gridded domains where more highly resolved results are required,
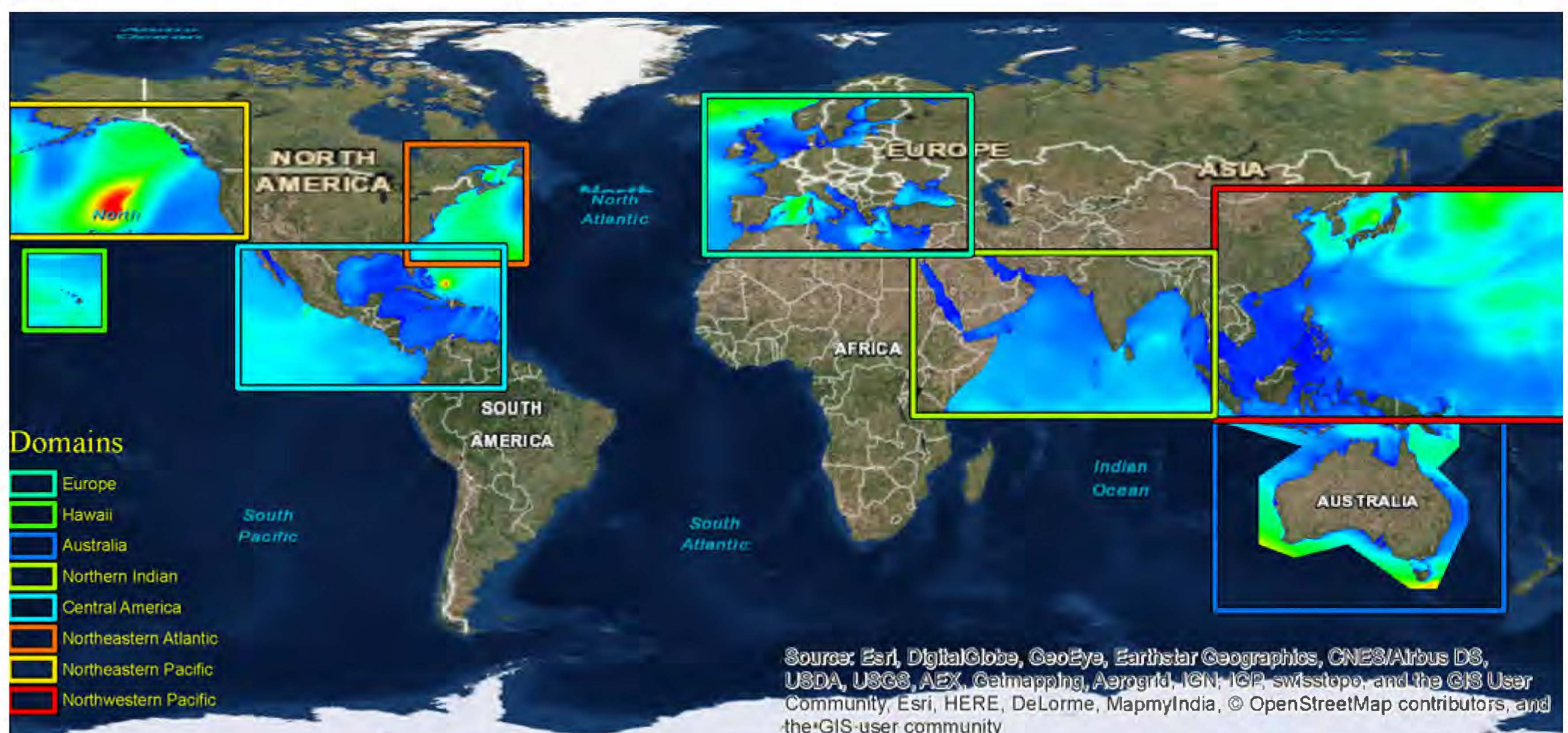
This represents the layout of the regional domains for an operational multigrid system. Each of the domains is filled with the significant wave height prediction valid for 1 October 2015.

(e.g., near coasts). Wave spectra are typically passed one-way from the coarser model after it has completed—and at temporally coarse (e.g., three hours) increments—through the boundaries to nested higher resolution domains. The multigrid capability passes wave energy between domains in both directions at more frequent time intervals with simultaneous integration of all grids, which increases the potential for more accurate results. Thus, when winds generated by a mesoscale meteorological model such as COAMPS are applied to a higher resolution WAVEWATCH III domain, this innovative feature allows other domains to benefit from the potentially increased wave energy. An example of the effect of this feature is depicted in the figure below where waves generated by Hurricane Joaquin in one domain are allowed to propagate to another ultimately affecting the eastern sea board.
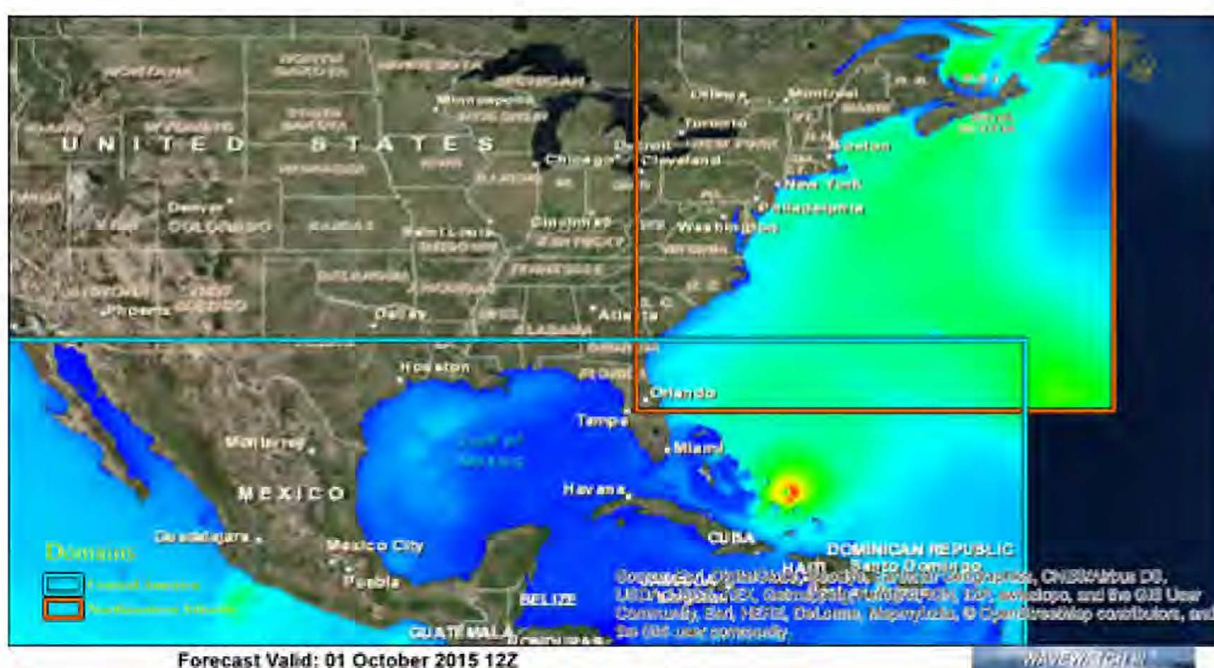
This shows wave heights on the waters surrounding Hurricane Joaquin. The colors, representing wave heights, show greater wave heights centered near the Bahamas.

Development Background

The WAVEWATCH model was originally developed at Delft University in the Netherlands. Its current form, WAVEWATCH III, was developed at NOAA's National Center for Environmental Prediction. The model is free and open source, with license restrictions. During the 2000s, the program evolved from code written by a single author into a community effort. A key enabler for the move toward a community-managed model has been a National Ocean Partnership Program for wave physics, funded primarily by the Office of Naval Research and NOAA. The latter provides the version-control infrastructure required for simultaneous development of the same code by numerous authors, including personnel from NOAA, Ifremer (France), the US Navy, the UK Met Office, Swinburne University (Australia), and others.
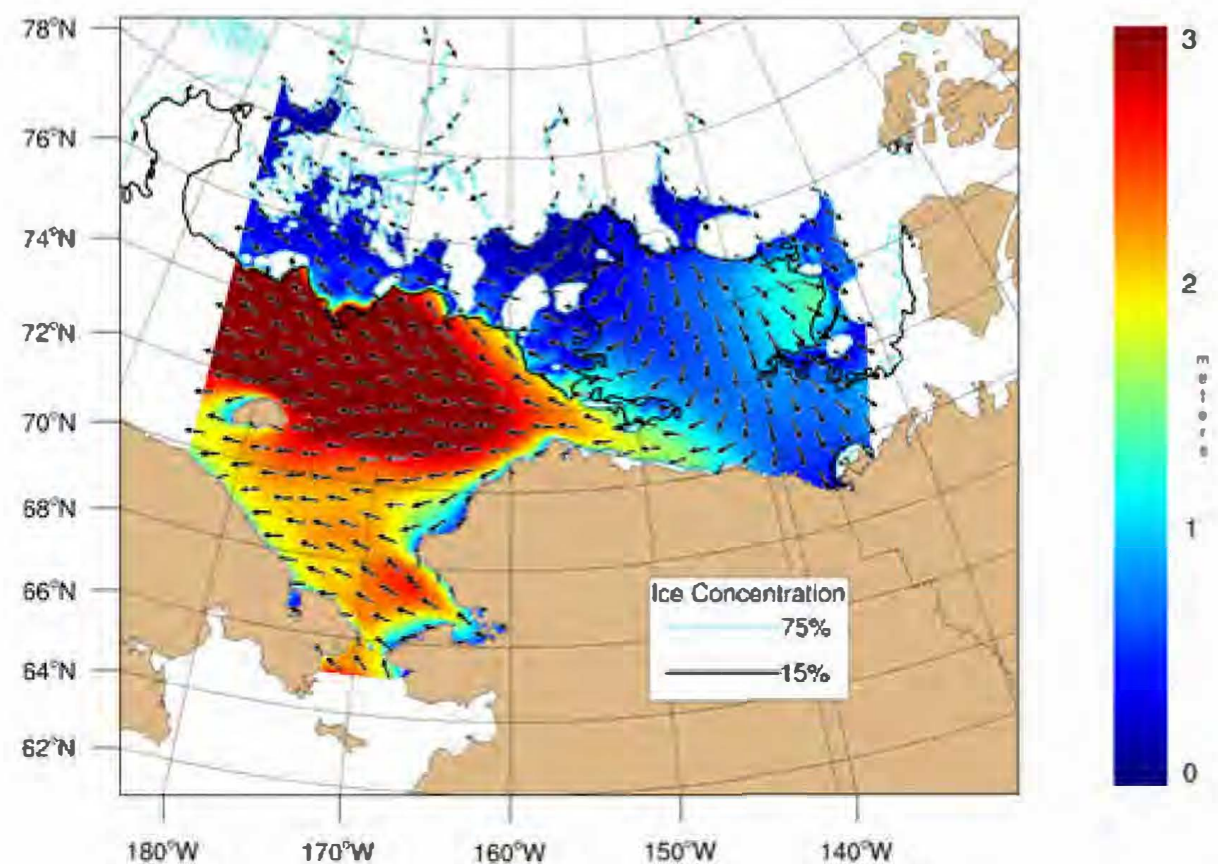
A sample product from WAVEWATCH III predicts wave conditions in the Arctic. For reference, the contours for ice concentration from the regional CICE ice model run at the Naval Research Laboratory are overlaid.

Using recent advancements in model physics, the latest model version can optionally represent certain source terms, including the effects of bottom friction, bottom scattering, sea ice, reflection from icebergs and steep shorelines, surf breaking, fluidized mud, and three-wave nonlinear interactions. In some cases, multiple options exist for the same physical process, allowing different theories, parameterizations, and numerical rigor. In addition to static bathymetry, the model optionally ingests several fields that may be non-stationary and non-uniform: surface currents, water levels, ice characteristics, 10-meter wind vectors, and air-sea temperature differences (to represent atmospheric stability). Unresolved islands and ice can be treated with a subgrid parameterization.

On the numerical side, WAVEWATCH III can perform computations on unstructured and irregularly structured grids. Propagation schemes using first-, second-, and third-order equations can be selected balancing accuracy against computational cost.

The timeliness of the operational runs of a wave model with such potentially complex configurations and diverse inputs is made possible with multiple options in parallel computing. On multiple processors, WAVEWATCH III computations can be distributed through message passing interface, with an innovative, two-phase domain decomposition of geographic and spectral grids during separate time steps for source-term calculation and geographic propagation, respectively.

Wave Predictions for the Arctic

The latest version of WAVEWATCH III has implemented new curvilinear gridded Arctic domains developed by NRL in response to a Navy requirement for wave prediction in the Arctic due to the recent decrease of ice cover in the summer and thus more open water. As participants in a Coast Guard operation in the Arctic, NRL demonstrated proof-of-concept operations providing real-time prediction products for atmosphere, ice and wave conditions. WAVEWATCH III was configured with curvilinear domains at 15 km and 5 km grid spacing using winds and ice from regional COAMPS and from the Navy's application of the Los Alamos Community Ice Code models, respectively. The propagation and dissipation of waves is affected by ice concentration. In this case, a threshold for ice concentration selected at 15 percent allows waves to propagate into the ice and then dissipate. At an ice concentration threshold of 75 percent, computational points are treated like land and no wave energy will penetrate. As USCGC *Healy* (WAGB 20) made its transit to the North Pole, predictions in ice concentrations became more critical to predict more precisely the sea state. The illustration above left depicts an example of a product of significant wave height and mean wave direction in the Chukchi and Beaufort Seas, including contours of ice concentration which was used as input into the wave model. These products were delivered twice daily on the NRL Monterey COAMPS on-scene web server.

Challenges for Fully Global Wave Prediction

This latest version of WAVEWATCH III lays the groundwork for the wave component of the Navy's Earth System Prediction Capability, which is a fully coupled atmosphere/ocean/ice/wave global prediction system. One of the challenges for efficient global coverage of wave simulations is resolving small features in the wave field that are caused by similarly small features in the forcing, e.g. ocean eddies and atmospheric mesoscale features, while not having to use an unreasonably small time-step, a common obstacle when solving numerical equations using a finite difference method. A spherical grid used for global coverage consists of meridians that converge toward the poles. If this type of domain were to extend too close to the poles, the meridians would narrow the grid spacing to a point that the propagation time steps would be impractically too small. A solution is a grid system where converging lines

occur where no computations will occur such as over land, thus the idea of using a tri-pole grid. The figure below illustrates how two of the poles of the tri-pole grid are connected by a seam. Each of these poles is located in the continents of North America and Asia, while the third pole is the South Pole. An alternative approach is to use the multigrid capability with a combination of two high latitude curvilinear domains covering the Arctic and Antarctic and a $\frac{1}{4}$-degree resolution mid-latitude domain that extends to about 55 degrees N and 55 degrees S that, relative to the tripole grid, provides even more uniform grid spacing, and thus better efficiency.
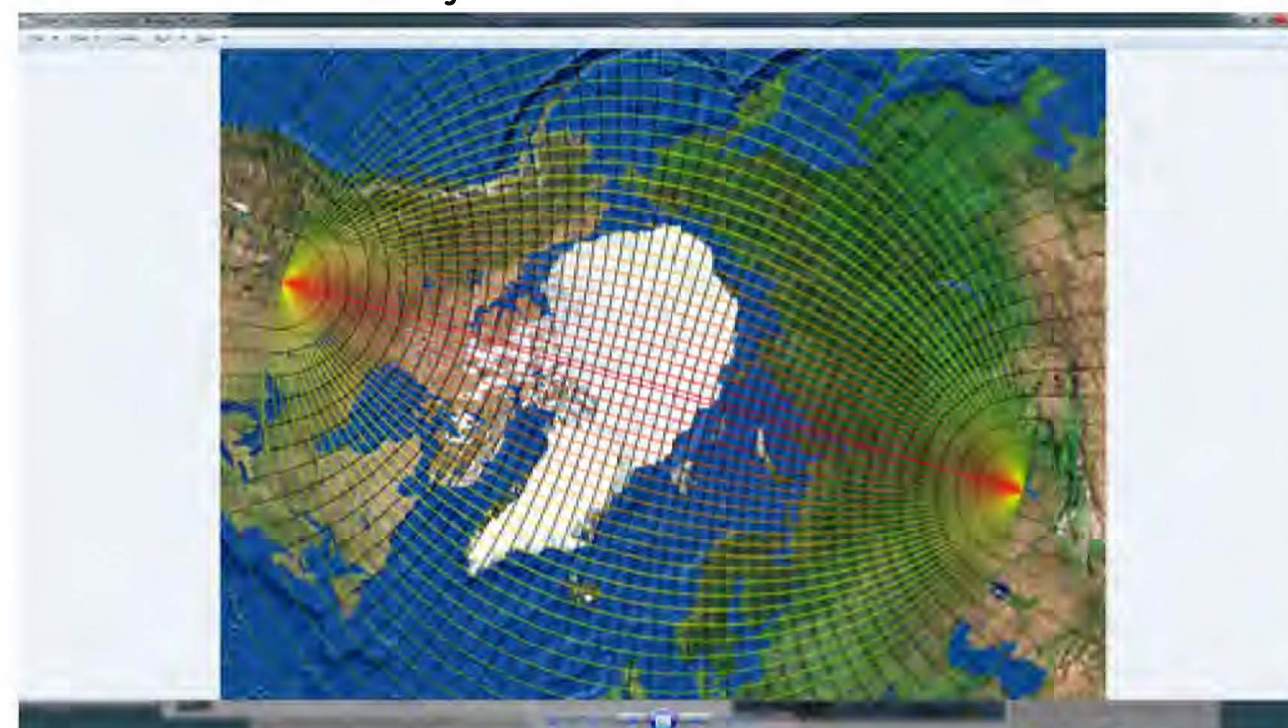
This tripole grid layout for WAVEWATCH III for the i- and j-indices is decimated to about every 15th grid point for easier illustration. The j-indices are color enhanced to bring out the seam between two poles. Part of the grid in the Northern Hemisphere is shown.

These strategies and capabilities just described are possible thanks to the latest technology in state-of-the-art wave modeling using WAVEWATCH III and cutting-edge, high-performance computing. On-going efforts within the research community will continue to bring forward-thinking technologies to bear in support of naval operations with up-to-the-minute wave and wave-related predictions.

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